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Recent Experience With Synthetic Hydrocarbon Lubricants for Spacecraft Applications

20 June 1995

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13. ABSTRACT (*Maximum 200 words*)

Synthetic hydrocarbon oils are a relatively new class of spacecraft lubricants. They offer several advantages over petroleum-based oils, such as lower volatility and lower reactivity. In this paper, we present four cases in which the performances of synthetic hydrocarbon oils in certain applications are compared to the performances of mineral oils and other synthetic oils and an experimental investigation of additive performance. In all cases, the performances of the synthetic hydrocarbon oils were superior.

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Contents

Figures

Tables

1. Introduction

The building and deployment of spacecraft is a relatively young business. Initially, spacecraft builders relied on previous experience in other areas, i.e., the automotive industry, to guide the lubrication of the various moving mechanical assemblies. Lubricants based on refined and distilled petroleum products were used extensively. Generally, the lifetimes of the early spacecraft were short, and the limitations of these lubricants were not a serious problem. As the applications have become more demanding and the lifetimes much longer, the limitations of petroleum-based lubricants, such as greater reactivity and higher vapor pressure, became more obvious. The development of synthetic oils alleviated some of the limitations, but opened up new areas of concern. An example is the perfluoropolyalkylether (PFPE) oil-based lubricants. They exhibit very low vapor pressures, have large viscosity indices, and are, for the most part, chemically inert. Because of these favorable properties, PFPEs were used in a variety of applications without a real understanding of their limitations. More recently, they have been shown to be poor lubricants in the boundary tribological regime, and their use in applications in which boundary conditions exist has been curtailed (Refs. 1, 2). The problem with PFPEs is that they are very poor solvents, and do not dissolve antiwear additives, the materials that help hydrocarbon lubricants perform much better under boundary conditions. The recent advent of synthetic hydrocarbon oils has resulted in a broader choice of lubricants for the spacecraft community. The poly-α-olefins (PAOs) and, more recently, the trialkylated cyclopentane (TAC) oils have many of the favorable properties of petroleum-based fluids, such as the ability to dissolve additives and thickeners to form greases. They are generally less reactive than petroleum-based fluids because the synthetic fluids do not have reactive impurities that limit their performance. They can also be tailor-made to possess low vapor pressure and controlled viscosity behavior. In this paper, we will present the properties of several of these fluids, screening test data in which their performances are compared to other materials, and orbital and/or life-test data in several types of moving mechanical assemblies.

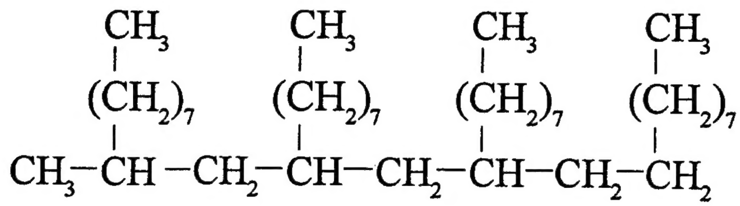
2. Oil Properties

Selected properties for three synthetic hydrocarbon oils are given in Table 1. The TAC oil (Pennzane), synthesized by Pennzoil Products, Inc., and the PAOs (Nye 179A and 188B) are available in a variety of formulations. Generally, mineral oils have higher vapor pressures, lower viscosity indices, and much higher pour points. Figure 1 shows the chemical structures for the PAOs and the TAC oils. PAOs are generally synthesized by polymerizing 1-decene. As a result, mixtures containing C20, C30, C40, etc. are obtained. During the processing, the double bond in 1-decene migrates, resulting in many isomeric branching possibilities. C40 without any double-bond migration is shown in Figure 1 for illustration purposes. The TAC is produced by a different synthetic approach. Approximately 90% is 1,2,4-tri(2-octyldodecyl)cyclopentane, and 10% is disubstituted cyclopentane. The trisubstituted compound has six chiral centers so that 64 stereoisomers are possible. A mixture of isomers is obtained with some isomers in greater proportion because of differences in stability. The properties of the TAC are fixed (although other alkyl-substituted cyclopentanes can be synthesized), whereas the composition of the PAOs can be adjusted by varying the proportions of the various molecular weight groups to achieve desired viscosity and vapor pressure values.

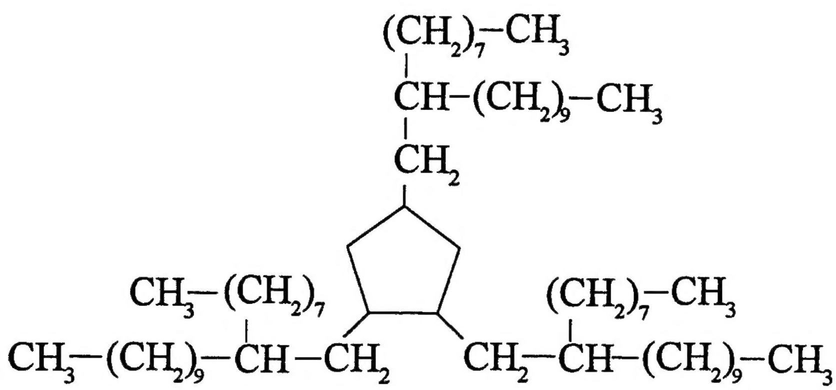
Table 1. Synthetic Hydrocarbon Oil Properties

Property		Pennzane	179a	188b
Viscosity, cs	100°C	14.7	5.8	14.5
	40°C	112	30	107
	-17.8°C	-[a]	780	4700
Viscosity Index		135	139	145
Pour Point, °C		-57	<-60	-55
Base Oil Vapor Pressure, torr	100°C	1×10^{-8}	1×10^{-5}	-[a]
	25°C	9×10^{-12}	3×10^{-8}	-[a]

a. Property data unavailable



PAO



TAC

Figure 1. Structural formulas for PAO and TAC synthetic hydrocarbon oils.

3. Applications

3.1 Harmonic Drive Actuator

The first use of the TAC oil on a spacecraft mechanism occurred on the bearings and gears of a harmonic drive actuator mechanism. The original lubricant, a PFPE (Krytox 143AB), failed to meet the design lifetime of the unit. For this application, pointing of sensors controlled by the actuators is critical, and success or failure is determined by the amount of backlash that the system develops. The Krytox 143AB lubricated life test developed unacceptable backlash prior to completion of one lifetime. The motion in the test was oscillatory at a speed of $2.5°s^{-1}$, with reversal of direction every 140° of output shaft rotation. The test requirement was 100 million degrees of travel (> 2× life) at the output shaft. A replacement lubricant with better boundary lubrication performance was required.

A series of screening tests was run at our facility and also by the contractor. Our current screening-test apparatus is described in the literature (Ref. 3). The original data were taken with the first, prototype unit that has since been refined and provided the basis for the design of a similar tester at NCT in England (Ref. 4). It is based on an eccentric motion that incorporates a high percentage of sliding that forces boundary lubrication conditions. The results of our screening tests are given in Figure 2. The TAC and PAO clearly outperform the PFPE. Based on these results and screening tests performed by the contractor, the TAC and a PAO were selected for further testing. The antiwear additives selected to be tested were lead naphthenate and antimony dialkyldithiocarbamate. A hindered bisphenol was used as the antioxidant. In life testing, the best performance was given by the TAC oil with 5% lead naphthenate and 1% bisphenol. At the end of 100 million degrees of travel, there was no change in the system backlash. The contractor concluded, based on the backlash and the condition of the bearings, gears, and lubricant, that the test could have run 10× the total test travel without exhibiting unacceptable backlash.

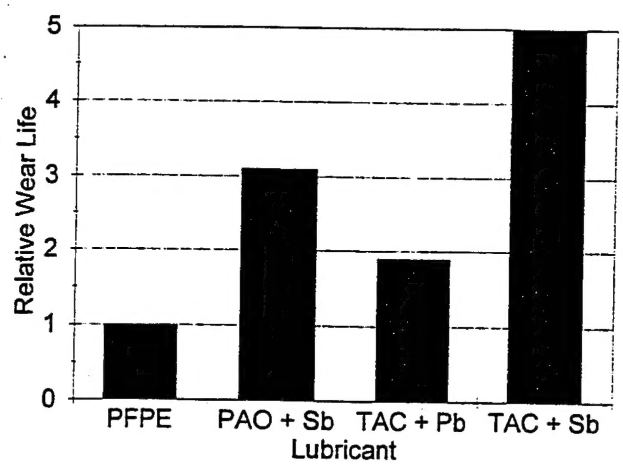


Figure 2. Screening test results for PFPE, PAO, and TAC oils.

The metal parts of the wave generator and motor bearings were analyzed using profilometry, scanning electron microscopy, and surface spectroscopies (Ref. 5). The metal parts were found to have lead- and carbon-containing layers on their surfaces. These layers were imparting the antiwear protection to the metal surfaces. In more recent tests, we found that thick layers of lead-containing substances are formed when lead naphthenate was used as an additive in our eccentric wear tester. This is undoubtedly due to the high temperatures generated by the severe boundary conditions in the screening tests (Ref. 6). Instead of metal wear causing a test failure, which is normally the cause of increased running torque (an increase in the running torque of 150% was used as the failure criterion), the thick lead-containing layer resulted in increased torque without any damage to the metal parts. As a result, our screening test underestimated the performance of the TAC oil with lead naphthenate additive under less severe conditions.

3.2 Oscillating Scanning Mechanism

Our group became involved with a spacecraft program in which anomalies in torque signatures were observed during testing of an oscillating scanner mechanism. Our initial testing was intended to assess the ball-bearing performance. We concluded that the bearings were adequate, but that the lubricant used in the application, a chloroarylalkylsiloxane (Versilube F-50), was not adequate for the boundary tribological conditions, and that the system achieved the design lifetime only through an extraordinary set of coincidences. The test data indicate that in the application the lubricant completely degrades during the first 2000 h of operation (most of it during ground and acceptance testing), and that the wear of the unlubricated metal parts results in complete relief of the bearing preload. On orbit, the function of the bearings is to center the shaft of the scanner, and the only load is the preload. The bearings fail to operate when the unlubricated cotton-phenolic ball retainer breaks because it must continuously change direction during the oscillatory motion. Bearing failure has occurred on orbiting spacecraft between 3 and 5 yr after launch. To achieve longer lifetimes for future missions, a better lubricant for the application needed to be selected and tested under simulated orbital conditions.

The lubricants investigated were the original F-50, Bray 815Z PFPE, and Nye 188B PAO. The F-50 and 815Z were unformulated. The 188B had 1% tricresyl phosphate (TCP) and 0.5% antioxidant. Screening test results indicated that the PAO was a better choice for this application. The lubes were tested in a facility that has been described in detail previously (Ref. 7). Briefly, it consisted of two bearing test cells that held two bearing pairs each. The drive mechanism, which was the engineering unit used by the spacecraft contractor, consisted of an inertial mass to simulate the optics and sensor array of the scanning mechanism. The scanner simulator oscillated through an arc of $\pm 57°$ at a frequency of ~6 Hz. The R2 test bearings were mounted in duplex pairs with a hard preload of 13.4 ± 2.2 N (3.0 ± 0.5 lb). The entire facility was housed in a vacuum chamber with test pressures of $\leq 1.3 \times 10^{-6}$ Pa ($\leq 1 \times 10^{-8}$ torr). The tests were run at ambient temperature.

The results of the life tests are given in Table 2. The F-50 oil test was declared a failure at 1500 h test time. Figure 3 shows the torque traces for the F-50 tests at the beginning of testing and at

Table 2. Oscillating Scanner Test Data

Oil	Wear Life, h
F-50	1500
815Z	2350
188B	30,000[a]

a . Test stopped to free facility, not because of test failure.

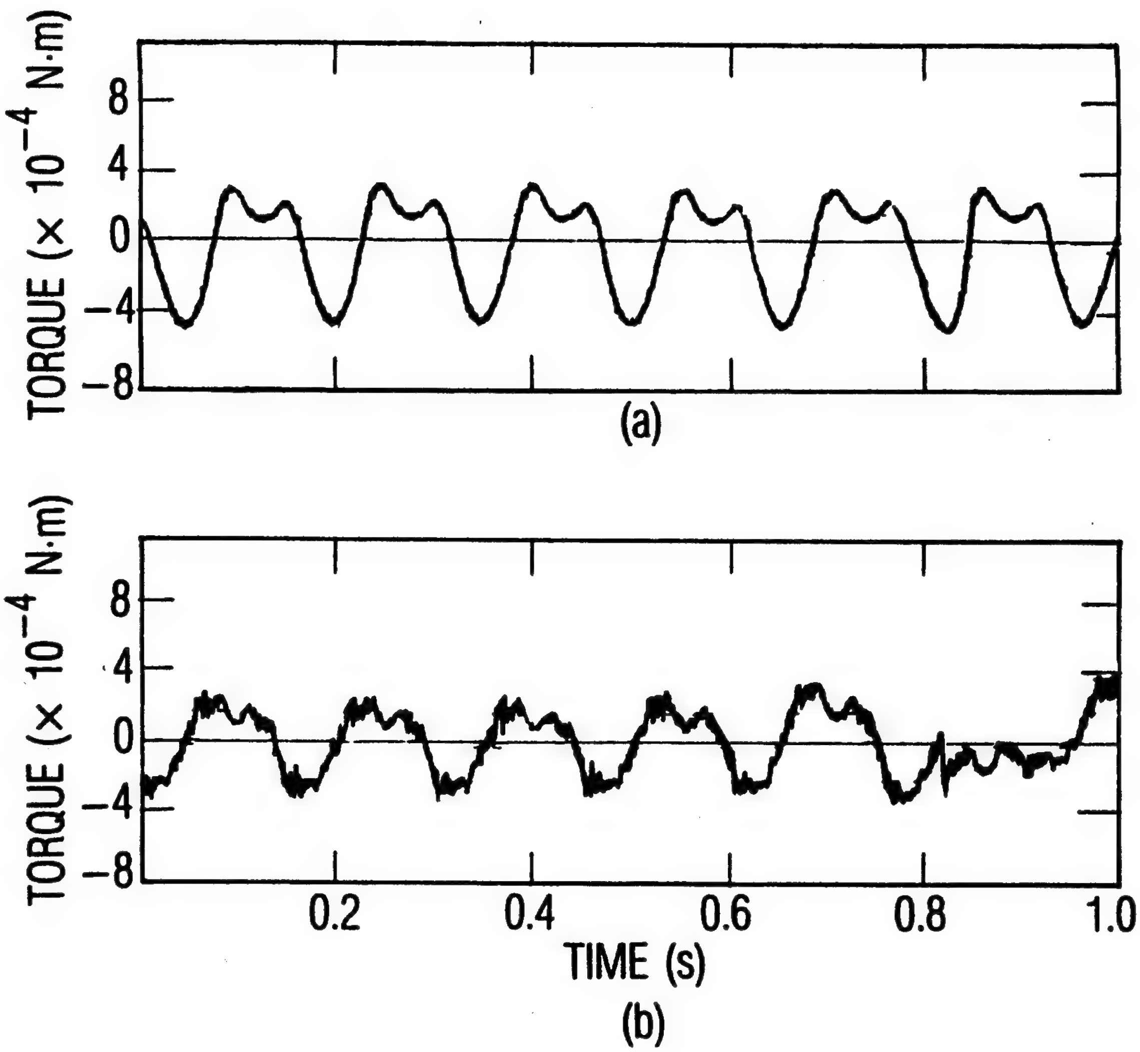


Figure 3. Torque traces for F-50 oil. (a) Initial trace; (b) trace taken at 1500 h. (Figure reprinted by permission of The American Society of Mechanical Engineers. All rights reserved.)

1500 h. There is considerable noise on the trace, and the amplitude has been reduced, indicating wear to the metal parts. The bearings were inspected at the end of testing. Three of four bearings in the test exhibited complete lubricant degradation. The fourth bearing showed signs of incipient degradation, but was still lubricated with wet oil.

Figure 4 shows torque traces for 815Z at the beginning of testing and at 2350 h, at which time the test was declared a failure. The torque amplitude had essentially gone to zero, indicating that the preload had been completely relieved through wear of the metal parts. As with the F-50 bearings, three of four 815Z bearings exhibited complete lubricant degradation, whereas the fourth still contained some wet oil.

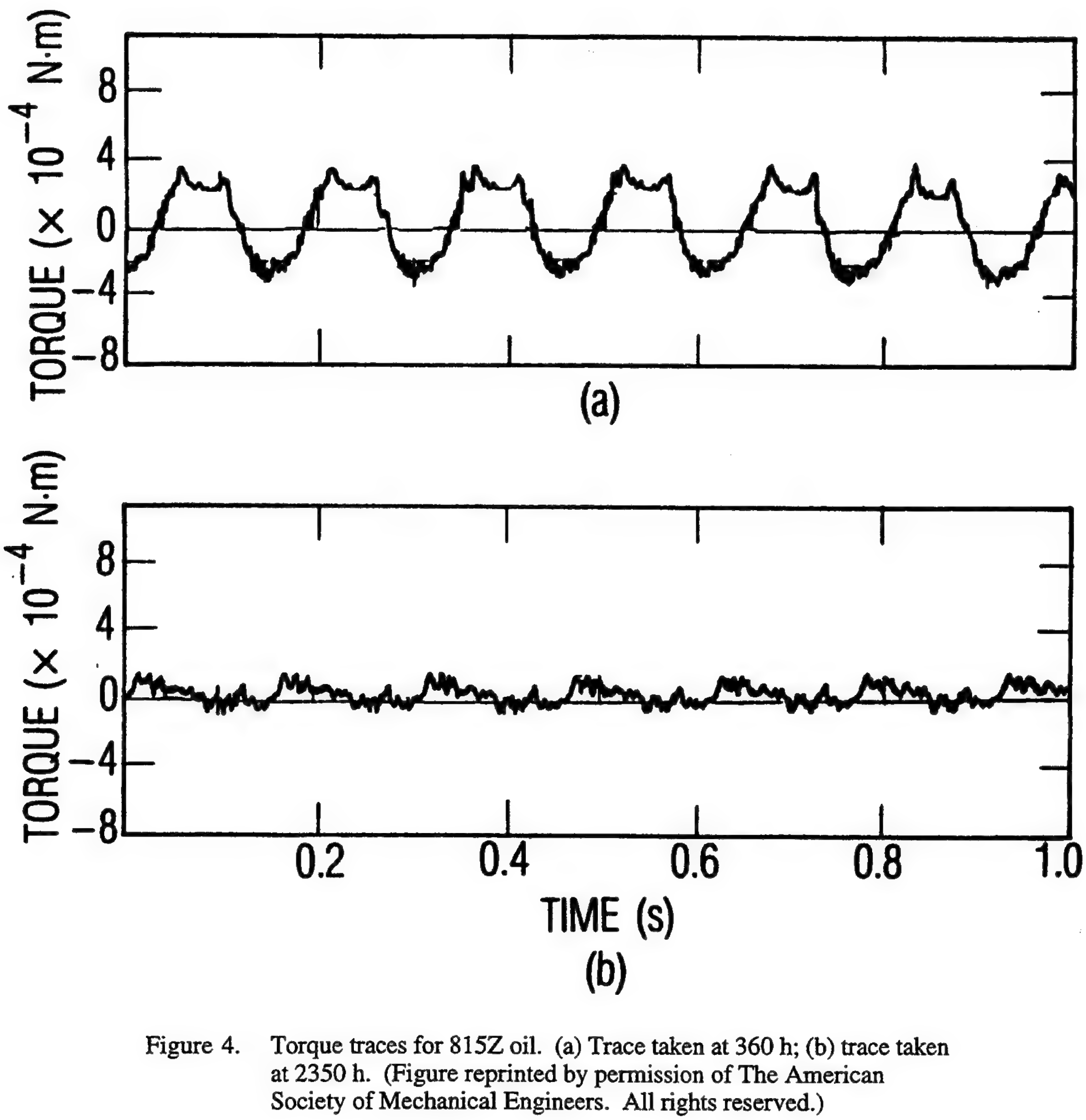


Figure 4. Torque traces for 815Z oil. (a) Trace taken at 360 h; (b) trace taken at 2350 h. (Figure reprinted by permission of The American Society of Mechanical Engineers. All rights reserved.)

Figure 5 shows the torque traces for the 188B tests at the beginning of testing and at 4300 h. There is very little change in the appearance of the traces, i.e., the amplitude is the same, but there is a small amount of "hash" on the trace at 4300 h. The test with 188B was run for 30,000 h. The test was terminated at this time to free up the facility for other tests. The torque traces looked essentially the same at the end of testing as they did at 4300 h. The bearings were well lubricated and exhibited insignificant lubricant degradation. In these tests, the bearings were open, i.e., they did not have shields, and the cartridges did not have labyrinth seals. After 3.5 yr at a chamber pressure of $\leq 1 \times 10^{-8}$ torr, the presence of oil in the bearings showed that evaporative loss was not a concern. A similar test was run at the contractor's facility. After 5.5 yr (~48,000 h), the test was stopped. There was no reduction in performance over the entire test.

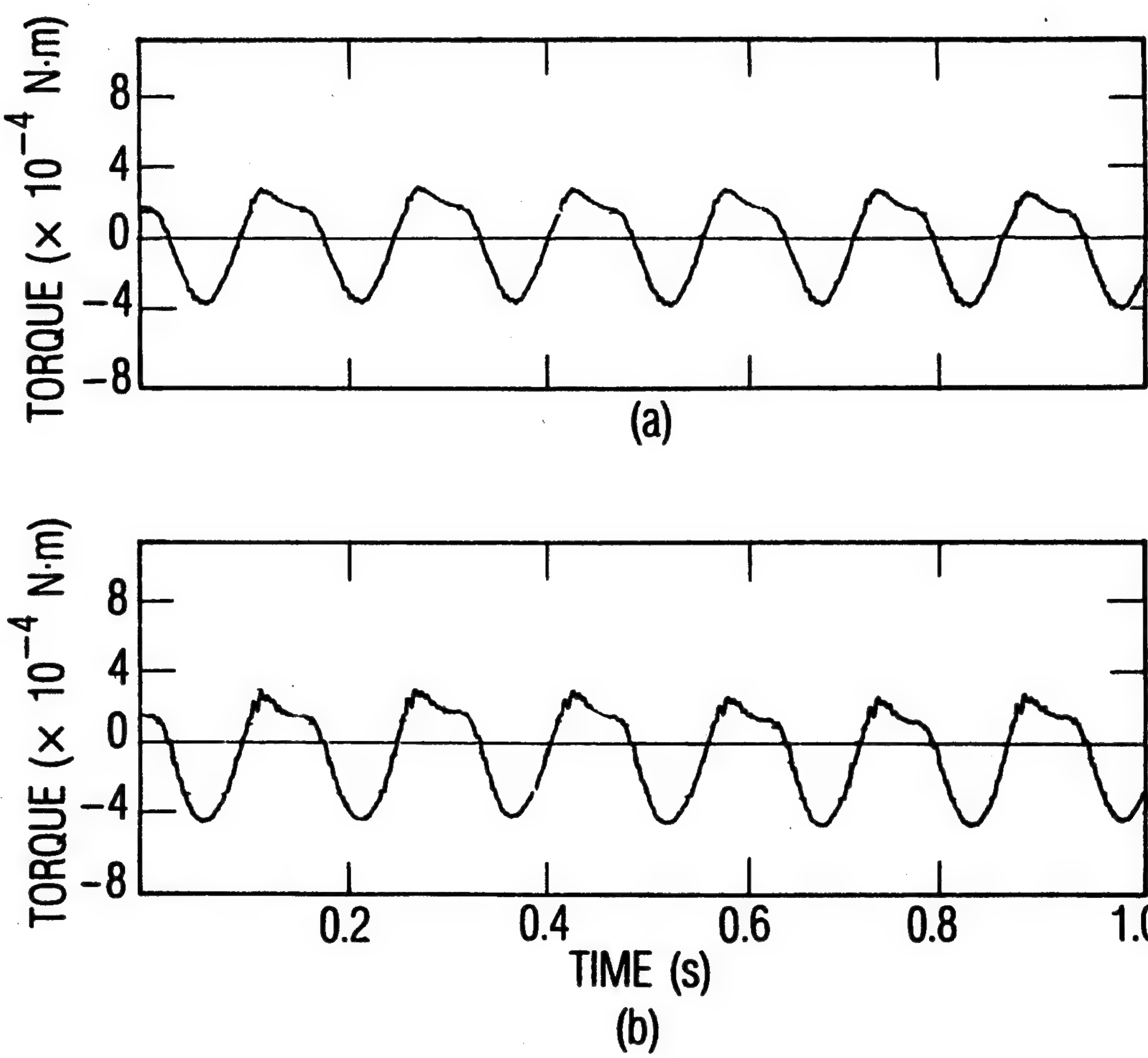


Figure 5. Torque traces for 188B oil. (a) Initial trace; (b) trace taken at 4300 h. (Figure reprinted by permission of The American Society of Mechanical Engineers. All rights reserved.)

These tests show the importance of having antiwear additives in applications in which boundary tribological conditions are present. The ability to dissolve additives, as well as the low vapor pressure and lack of reactivity of the synthetic hydrocarbon oil, Nye 188B, were the primary reasons that the test with this lubricant was successful. Recently, two satellites have been launched with this oil in the scan bearings, and performance is nominal.

3.3 Additive Studies

Much of the enhanced performance of the synthetic hydrocarbon fluids has been attributed to their ability to dissolve effective boundary additives, such as Pbnp and TCP. While Pbnp has a low vapor pressure ($<1.3 \times 10^{-7}$ Pa at 20°C), TCP is fairly volatile ($\sim 1.3 \times 10^{-3}$ Pa at 20°C). The additive was likely lost from the PAO lubricant in the above study in a relatively short time, and will be lost from unsealed spacecraft mechanisms as well. In an attempt to establish a protective film, bearing components are often treated in a TCP bath prior to lubrication. We performed tests with the eccentric test fixture to establish the performance of TCP in the TAC oil and determine the value of the surface treatment. In the tests described here, the additive used was actually trixylenyl phosphate (TXP), which is very similar to TCP.

Figure 6 shows lubricant performance in the eccentric test fixture under a variety of lubrication conditions in vacuum. Compared are the results for the additive alone (A), the unformulated TAC (B), the TAC with 1% TXP (C), and unformulated TAC with pre-treated components (D). These results clearly demonstrate that, relative to pure TAC, formulating the oil with the additive provides a tenfold increase in test life, while the bearing pretreatment increases life by a factor of less than 2. The final test result on the chart (E) provides some very interesting information. In these tests, the bearings were run for 180,000 revolutions with the formulated oil, and then

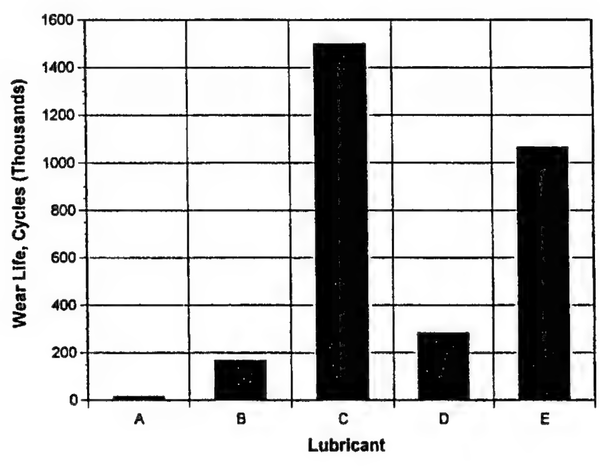


Figure 6. Wear test results for TAC oil with TXP additive. A—additive alone; B—unformulated TAC; C—TAC + 1% TXP; D—pretreated parts with unformulated TAC; E—180,000 cycles with formulated TAC + ~900,000 cycles with unformulated TAC.

stopped. The bearings were cleaned by rinsing with heptane, re-lubricated with unformulated TAC, and run to failure. The tests under condition (E) lasted almost as long as those conducted entirely with formulated oil, and much longer than the tests with pre-treated components. (The conditions used for these eccentric tests were harsher than for other tests presented in this paper, and the absolute wear lives among the various tests must not be compared.)

The additive performance tests lead to several conclusions. First, having the additive formulated in the lubricant provides greater benefits than bearing pre-treatment. Second, the protective film generated by the operating bearing is more effective than that formed by pre-treatment. Third, the additive does perform under vacuum conditions. In results not presented, there was an even greater extension of life under these conditions when both pre-treatment and formulated oil were used. In addition, test results show that using less volatile phosphate esters can also extend the test life under the harsh boundary conditions. These tests have demonstrated the need for additives in synthetic oils, and have shown that protective films form early in life due to the chemical interactions in the boundary contact. However, the need for lower vapor pressure additives is also clear if the benefits of extremely low vapor pressure lubricants, such as the TAC oil, are to be fully realized.

3.4 Reaction Wheel Oil Loss

Reaction wheel assemblies (RWAs) that were stored for long periods (5–10 yr) exhibited loss of lubricant from the bearings. Analysis of the residual lubricant in the bearings revealed that the lubricant suffered evaporative loss as well as loss due to surface migration (creep). The oil used in the application was SRG-40, a fairly volatile, highly refined mineral oil. The wheels were stored and operated with a sealed atmosphere of helium + 2% oxygen at a pressure of 0.5 atm. The oil was formulated with 1% TCP + 0.5% antioxidant. It has been postulated that oxygen is needed in the atmosphere of the bearings to convert exposed metal surfaces to their corresponding oxides in order for TCP to react with the surfaces and function properly. We believe that oxygen is not required for TCP to do its job and, in fact, can be detrimental to the performance of the lubricant once the antioxidant has been lost and/or used up. There was also concern that the SRG-40 oil would be lost quickly from the bearings on orbit if there was a leak in the RWA housing causing the background pressure in the RWA to drop to the orbital pressure in the spacecraft. We performed screening tests to select a replacement lubricant and to assess the effects of the oxygen on the performance of the wheels.

The three lubricants tested were SRG-40, Nye 179A, and Nye UC-7. The third lubricant is a synthetic polyol ester oil. The viscosities of the two synthetic oils are slightly higher than that for SRG-40, but low enough that there are no concerns about drag in the wheel. (The viscosities at 300K are 30, 41, and 46 cs for SRG-40, 179A, and UC-7, respectively.) Both of the synthetic oils are considerably less volatile and have significantly lower pour points than SRG-40. All three lubricants were formulated with TCP. The screening tests were performed on our eccentric test facility. The speed was 1800 rpm, the load was 3 or 4 lb/ball, and the lubricant quantity was 60 µL. Tests were run with four different atmospheres: vacuum of $<1.3 \times 10^{-5}$ Pa($<1 \times 10^{-7}$ torr), one-half atmosphere of a 2% oxygen-in-helium mixture, one-half atmosphere of pure helium, and 7 torr of pure oxygen. The pure oxygen was used to determine if we could isolate the effects of oxygen on the performance of the TCP.

Figure 7 shows the relative performances of the three oils in vacuum and in the 7-torr oxygen environment. (The 179A was not tested in the oxygen environment.) Two points can be made regarding these data. First, the synthetic oils performed significantly better in vacuum than did the SRG-40. However, we feel that this is not due to large differences in lubricity or the capability of the oil to provide adequate lubrication. Rather, it is a reflection of the higher vapor pressure of the SRG-40 oil. Under the test conditions, a large percentage of the oil is lost by evaporation. Gas chromatographic analysis of the residual oils in the tests confirmed that the SRG-40 had undergone considerable evaporative loss during the testing. There was very little evaporation of the synthetic oils. Second, the oxygen environment had a profound effect on the UC-7 oil. While the performance of the SRG-40 was better in 7 torr of oxygen than in vacuum (although this is probably due to a reduction of evaporation), the UC-7 oil performed poorly in oxygen. The presence of oxygen in the operating environment resulted in higher torque, more torque noise, and reduced wear life compared to vacuum conditions for UC-7.

Figure 8 shows the relative performances of the three oils under one-half atm of helium at both 3 and 4 lb/ball loading and in the one-half atm of 2% oxygen in helium at 4 lb/ball loading. In general, these tests ran much longer than the other tests because the presence of the higher background pressure reduced evaporation and allowed the bearings to operate at a lower temperature due to heat conduction by the gas. The tests of SRG-40 in helium and in the helium-oxygen mixture confirmed the results obtained in the other tests for UC-7: the presence of oxygen resulted in a reduced performance relative to that in the pure helium environment. In the pure helium environment, the UC-7 was the only oil that failed consistently. In contrast, the tests with

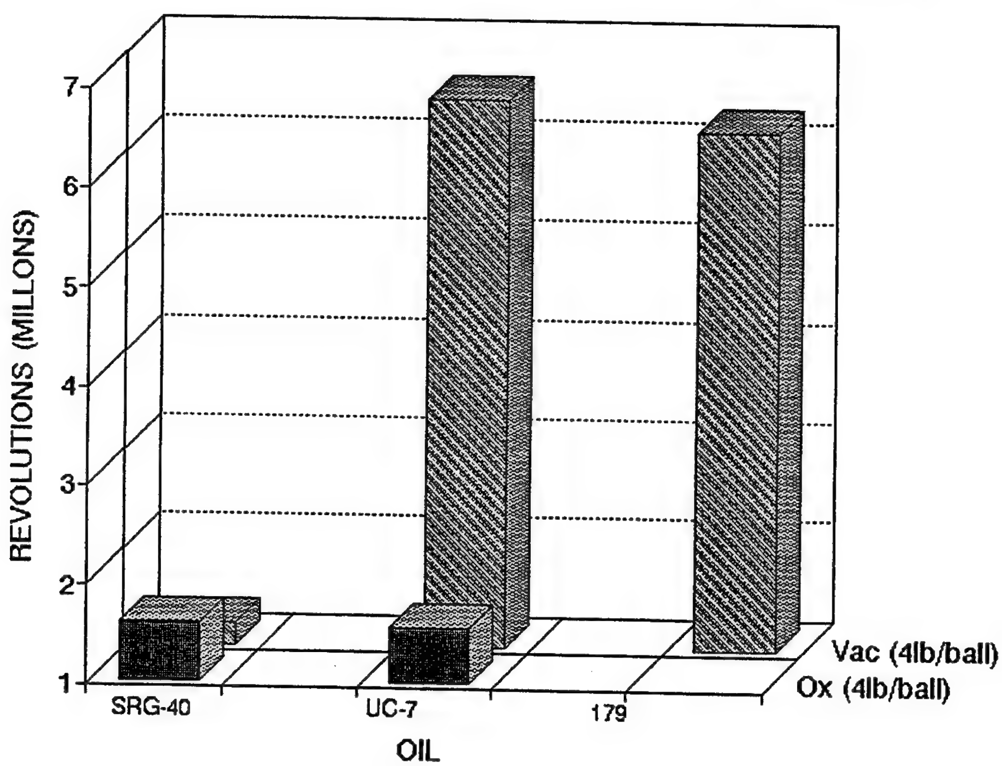


Figure 7. Vacuum and 7 torr oxygen screening test results.

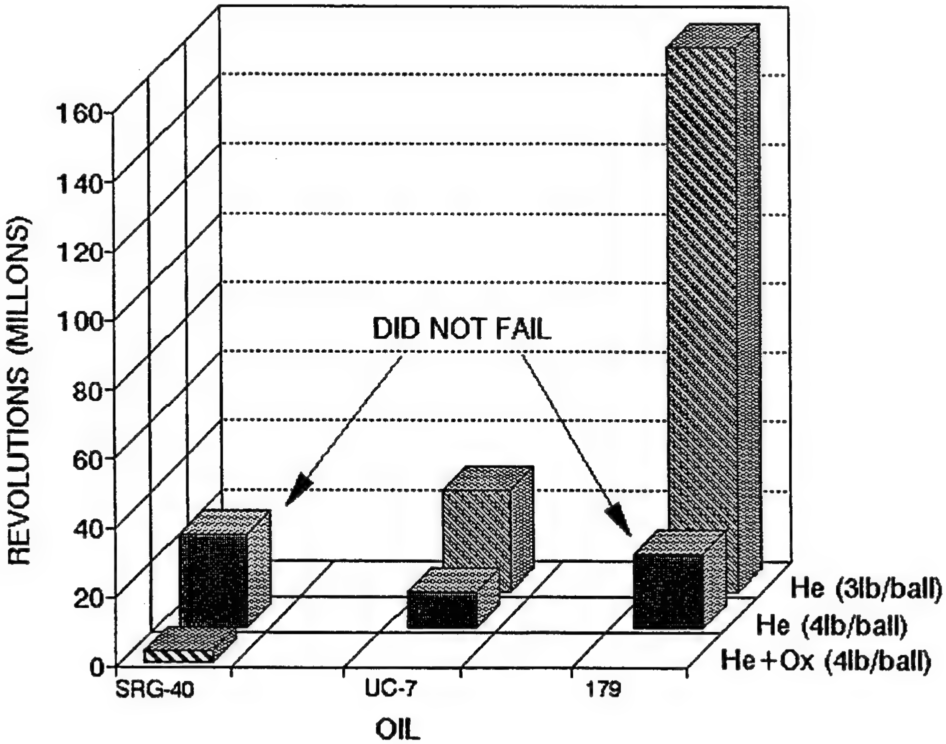


Figure 8. One-half atmosphere screening test results.

the SRG-40 and 179A were either terminated before failure, due to time constraints, or were run for a great length of time to failure (179A).

Surface analysis and profilometry of the metal parts following the tests yielded information pertaining to the relative performances of the oils. There were comparable layers of phosphorus-containing material on the metal surfaces of the bearings from the tests of both SRG-40 and 179A. On the other hand, only minute traces of phosphorus were detected on the metal parts from the UC-7 tests. Thus, it appears that the ester oil, or ester oil degradation products, competes with TCP for surface sites, but the surface film formed by the ester is not as effective in preventing wear as that formed by TCP . The results of the profilometry analysis confirm this conclusion. There was considerably more metal wear in the tests with UC-7 than with either of the other two oils. Furthermore, the metal parts in the 179A tests had less wear than the metal parts from the tests with SRG-40.

The results of the screening tests and the post-test analyses of the test components point toward 179A as the superior oil for this application. Its performance in vacuum was far better than SRG-40, and its performance in helium was the best of the three oils tested. The use of oxygen as a component in the fill gas of reaction wheels was determined to be unnecessary and generally detrimental to the performance of the lubricants.

3.5 Wheel Bearing Retainer Instability

New and future satellites will place more demands on the momentum storage devices. More momentum will require higher speed and/or more rotor mass. This, in turn, places higher demands on the wheel ball bearings. In several programs, the requirement for more momentum has resulted in episodes of retainer instability due, most likely, to insufficient lubrication at the ball/cotton-phenolic retainer interface. These episodes increase in frequency and duration until the bearing system and the wheel fails. Providing adequate lubrication to the ball/retainer to postpone or eliminate the advent of retainer instability is one of the challenges facing spacecraft programs.

Instability events can be typified by large ball/retainer and retainer/land forces that disrupt the normal retainer motion and excite high-energy vibrational modes in the retainer. The large forces involved eventually lead to ball skidding, higher ball bearing operating temperatures, and, in some cases, fracture of the retainers. We believe that the events are instigated by increases in the ball/retainer coefficient of friction beyond a threshold value. We undertook a study of retainer instability phenomena due both to excess and insufficient lubrication. Retainer instability due to excess lubrication is not generally considered to be a destructive phenomenon. In this discussion, we will concentrate on instability due to insufficient lubrication and the advantages offered by synthetic hydrocarbon lubricants.

A pair of 305 angular contact bearings with cotton-phenolic retainers, normally used in a control-moment gyroscope application, were used in the study. For the purpose of these tests, the bearings were modified to allow for addition of lubricant during operation. The bearings were run at a speed of 9800 rpm and an axial load of 89 N (20 lb). This load results in a contact stress of 1 GPa (150 ksi). The lubricants used in the testing were SRG-60 and KG-80, two highly refined mineral oils, and the synthetic oils, TAC and the PAO, 188B. The assembled bearings were prepared by Soxhlet extraction using heptane solvent to remove residual oil from the retainer and the metal parts. Once cleaned, the bearings were soaked in a 50:1 heptane:test oil solution for 10 min. The bearings were removed from the solution, and the solvent was allowed to drain and evaporate, leaving a thin oil film on the bearing parts. The amount of oil was considered to be barely sufficient to sustain bearing operation in the starved, EHD regime, and would lead to retainer instability in relatively short operating times.

The tests were typically run by slowly ramping the bearing speed up to 9800 rpm. Once the bearings reached constant temperature (generally 40–60 min), acquisition of bearing performance data (bearing torque) was initiated. The bearing torque was continuously monitored. The bearing instability events were signaled by large torque excursions, increased operating temperature, and chirping and grinding noises. When an event occurred, the bearing was allowed to run for 5–10 min in order to record the event. After the event had been captured, 50–100 μL of test oil was injected into each bearing. This was done to study the response of the unstable bearing to addition of oil and also to prevent damage to the metal parts.

Figures 9 and 10 show typical torque vs time traces for KG-80 and TAC, respectively. It is clear that we can induce retainer instability events in the laboratory. Using the 50:1 solvent:oil mixtures, both of the synthetic hydrocarbon oils exhibited near-nominal performance for 20 h or more of running time. The tests were stopped without inducing instability with these oils. On the

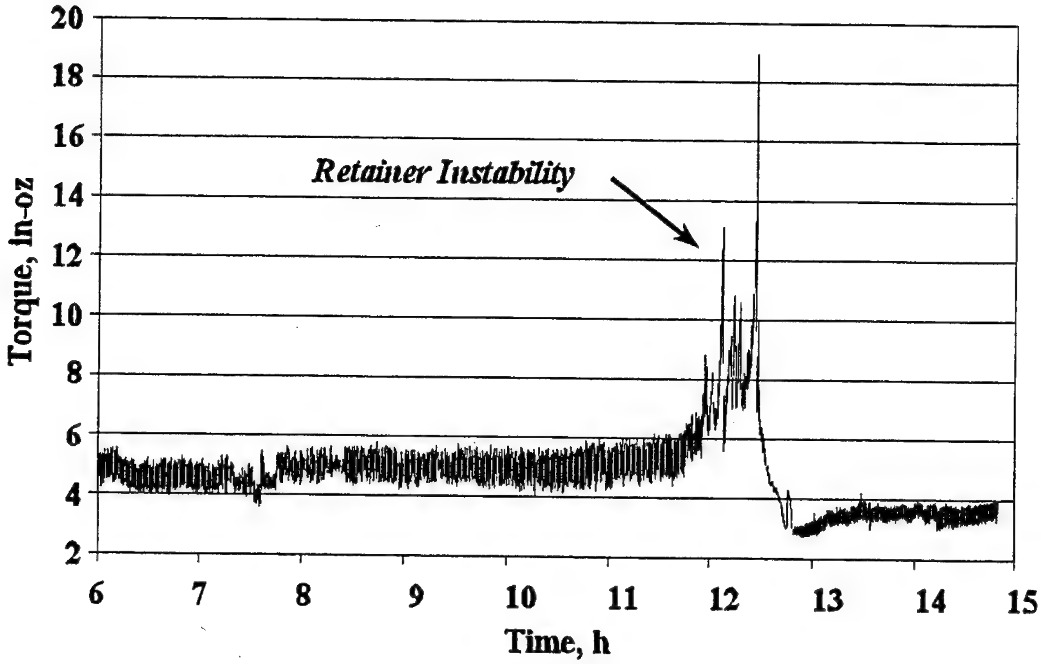


Figure 9. Torque vs time trace for KG-80 retainer stability test.

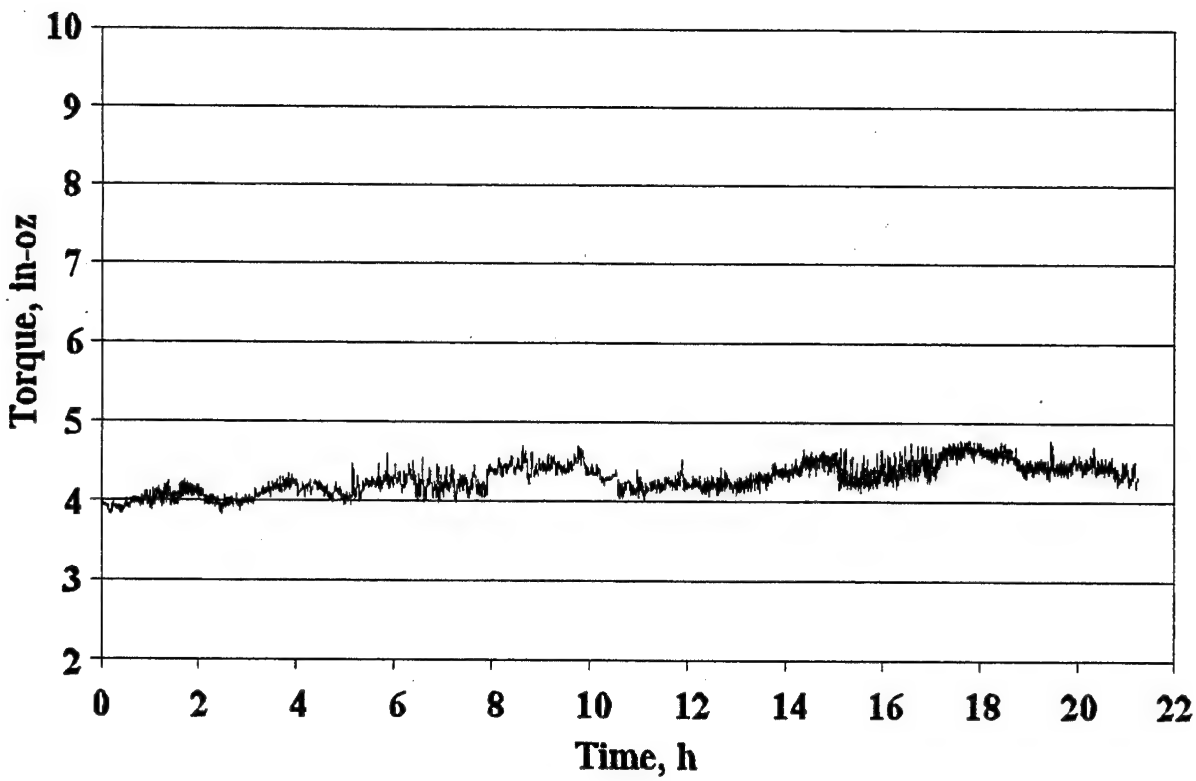


Figure 10. Torque vs time trace for TAC retainer stability test.

other hand, in the tests conducted on the mineral oils, instability occurred in the 2–12 h time range. In order to induce instability using the synthetic oils in a reasonable test time, it was necessary to increase the ratio of solvent to test oil to 70:1. Thus, it is clear that the synthetic oils provide superior resistance to retainer instability under starved conditions. In all cases in which instability was induced, the addition of oil to the bearings during the event had an immediate effect on the bearings. All symptoms of instability quickly disappeared. Generally, within 20 min, the torque and temperature returned to pre-event levels, or even lower torque.

The significance of these tests is twofold. First, we have demonstrated that we can induce instability in laboratory test so that the phenomenon can be studied. Second, the data from these tests demonstrate the overall superiority of the synthetic lubricants over mineral oils in severe operating environments.

4. Summary and Conclusions

We have presented four studies in which the performances of synthetic hydrocarbons were compared to mineral oils or to other synthetic oils. In all cases, the synthetic hydrocarbons exhibited superior performance. In comparison to mineral oils, the synthetic hydrocarbon oils have lower vapor pressures and less reactivity, and appear to have better frictional characteristics. We have yet to encounter an application in which a synthetic hydrocarbon oil did not perform as well as or better than a mineral oil. With regard to the other synthetic oils, PFPEs and polyol esters, the synthetic hydrocarbons, with appropriate additives, performed better under boundary tribological conditions. Conventional additives performed adequately. However, lower vapor pressure materials should be sought to complement the synthetic oil base stocks.

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